PARTICLE BEAMS FOR PLASMA HEATING

Frank J Wessel
SAFEnergy Inc., Irvine, CA

ARPA-E Fusion Workshop
New Orleans, LA
17 March 2023

CHALLENGES TO FUSION POWER

Scientific challenges

stability, scalability, current drive,
heating, fueling, magnetic beta, power balance

Engineering challenges

fuel cycle, first-wall materials,
energy capture/recovery

Commercialization challenges

COE, ROI, public acceptance, environmental

PARTICLE-BEAM SOURCES

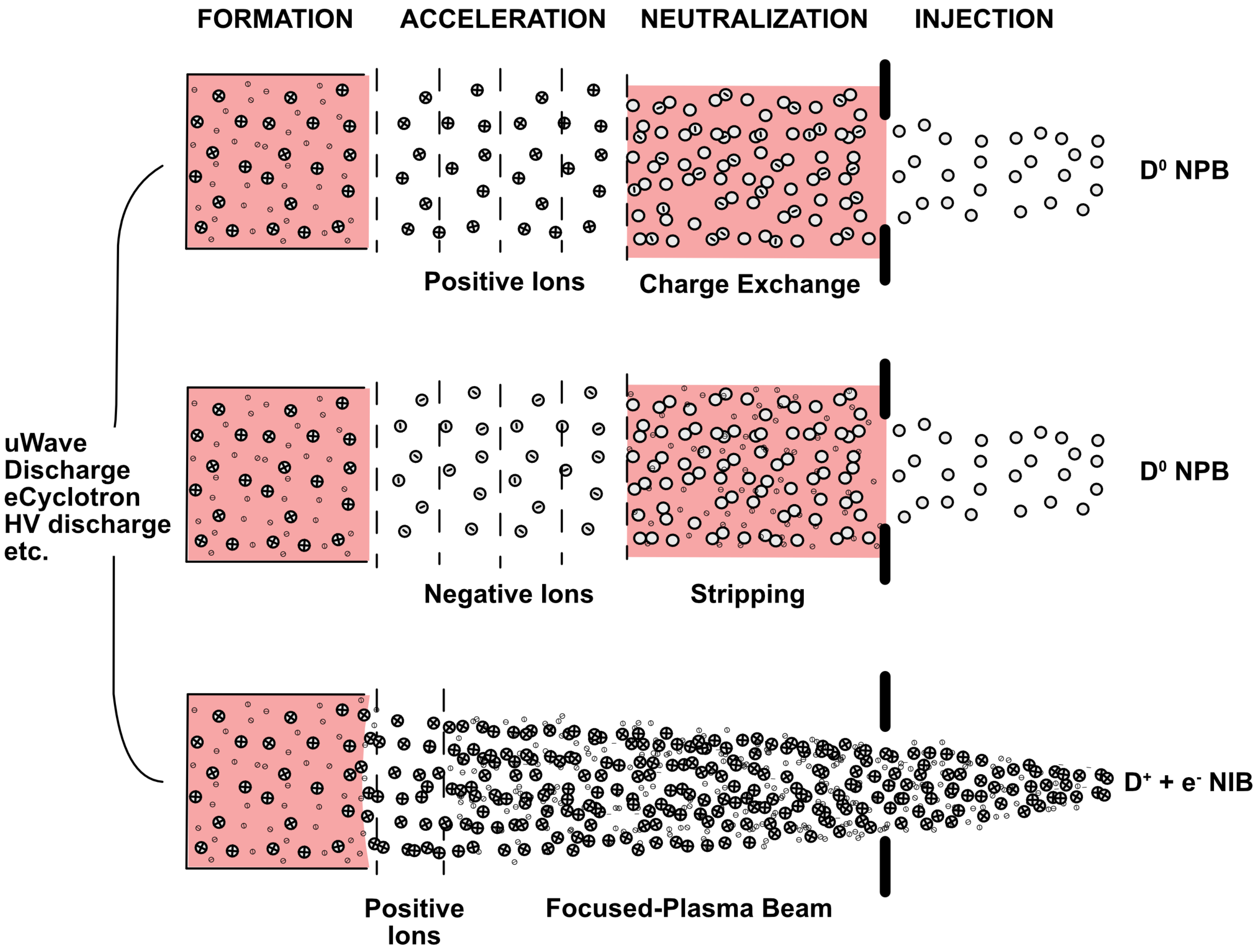
Three types to consider:

Positive-Ion Source,
Neutral-Particle Beam
$D^+ \Rightarrow D^0$

Negative-Ion Source,
Neutral-Particle Beam
$D + e^- \Rightarrow D^- \Rightarrow D^0$

Charge- and Current-
Neutralized-Ion Beam

$D^+ + e^- \Rightarrow D^+ + e^-$



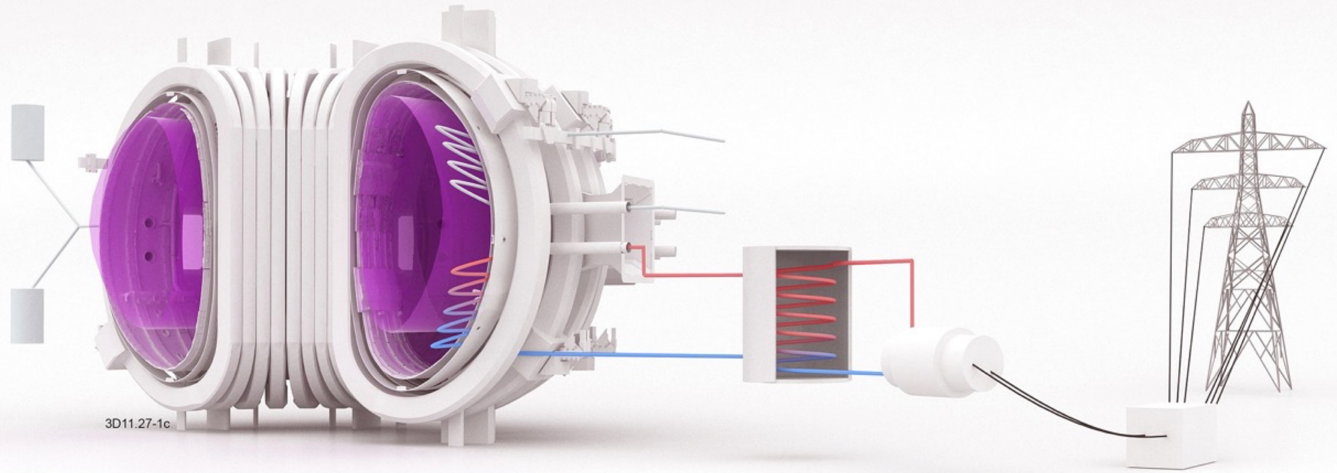
CHALLENGES: PARTICLE-BEAM HEATING

The use of a low efficiency ext. heating source decreases the reactor gain,

$$\mathbf{Q} \approx {E_{nuclear}}\Big/\left(E_{heating} + E_{losses}\right)$$

Similarly, high efficiency sources increase the reactor's global efficiency

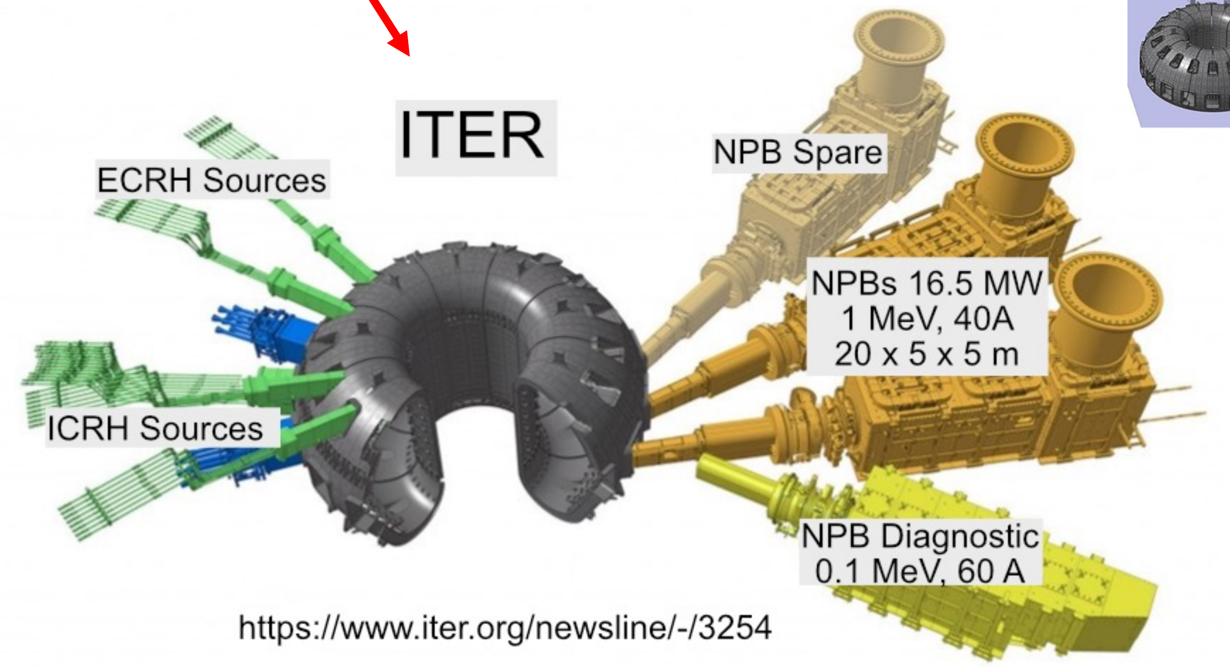
$$\epsilon = E_{operate}/E_{heating} \quad > 60\ \%$$

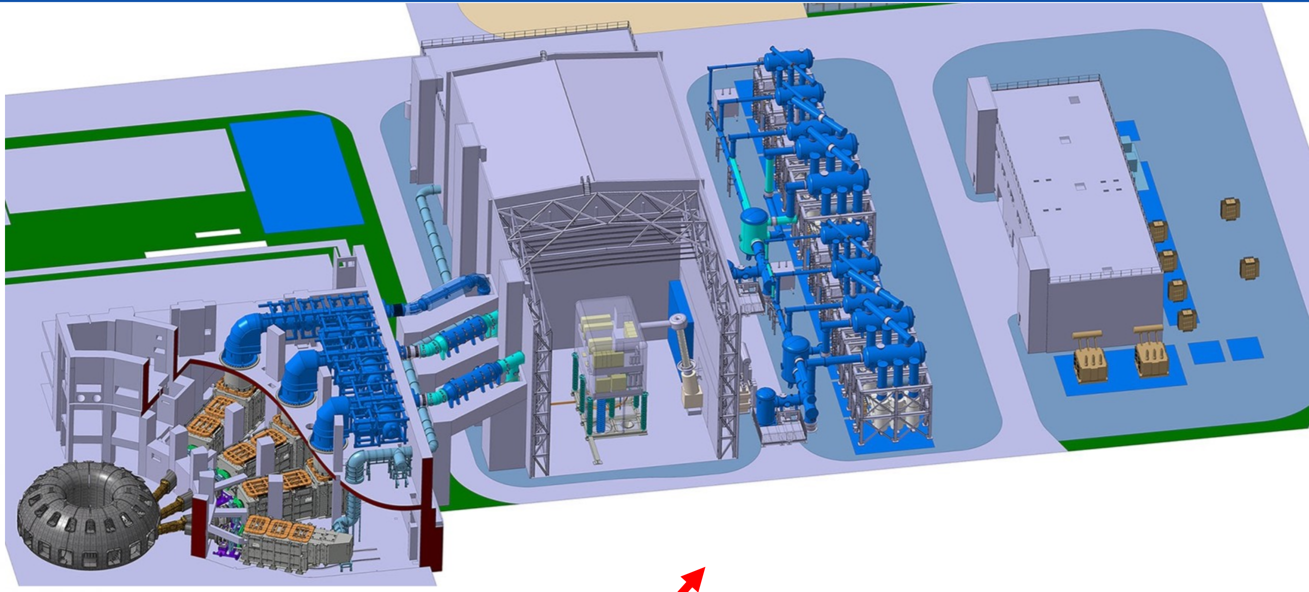


Euro-Fusion.org

CHALLENGES: PARTICLE-BEAM HEATING

Even as ITER is an experimental device, we can appreciate the magnitude of the challenge by considering the size of the beam heating sources.





Moreover, these heating sources need external electric power sources, which have an even larger scale and dwarf the size of the reactor.

NEUTRAL-PARTICLE BEAM (ITER)

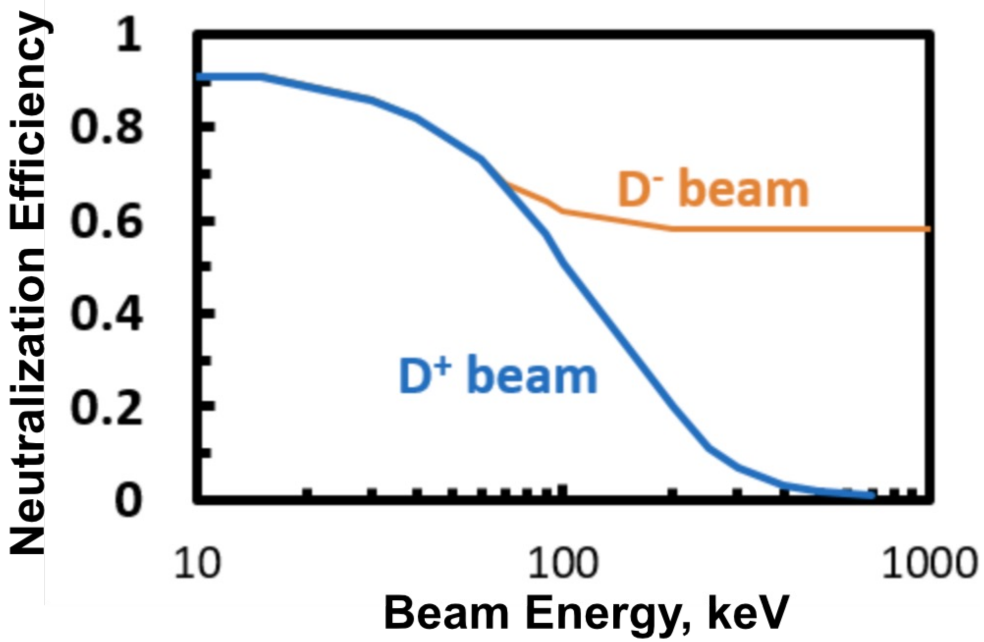
Large-size, dense-fusion plasmas require the use of high-energy particles for deep plasma penetration

Reactor-scale, neutral-particle beams use negative-ion source technology, since the efficiency of positive-ion sources are too low

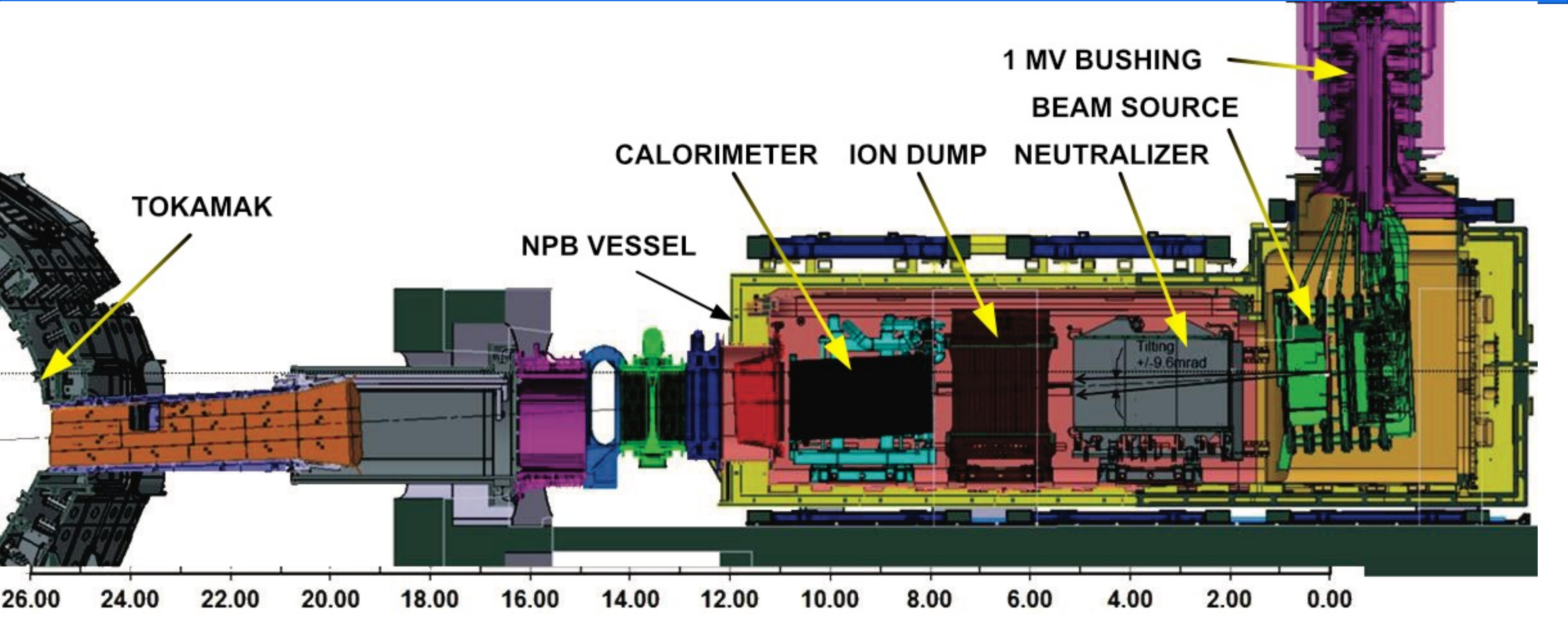
NPBs used on ITER are 1 MeV, 40 A, $200\ A/m^2$, 1m x 1m aperture, 10-minute pulse duration

No NPBs assembled to date have demonstrated continuous-duty operation

D+ sources are not suitable for fusion reactors



NEUTRAL-PARTICLE BEAM (ITER)



Hemsworth, R. S., and Boilson, D. AIP Conf. Proc. 1869, 1 (2017), 060001.

NEUTRAL-PARTICLE BEAM (ITER)

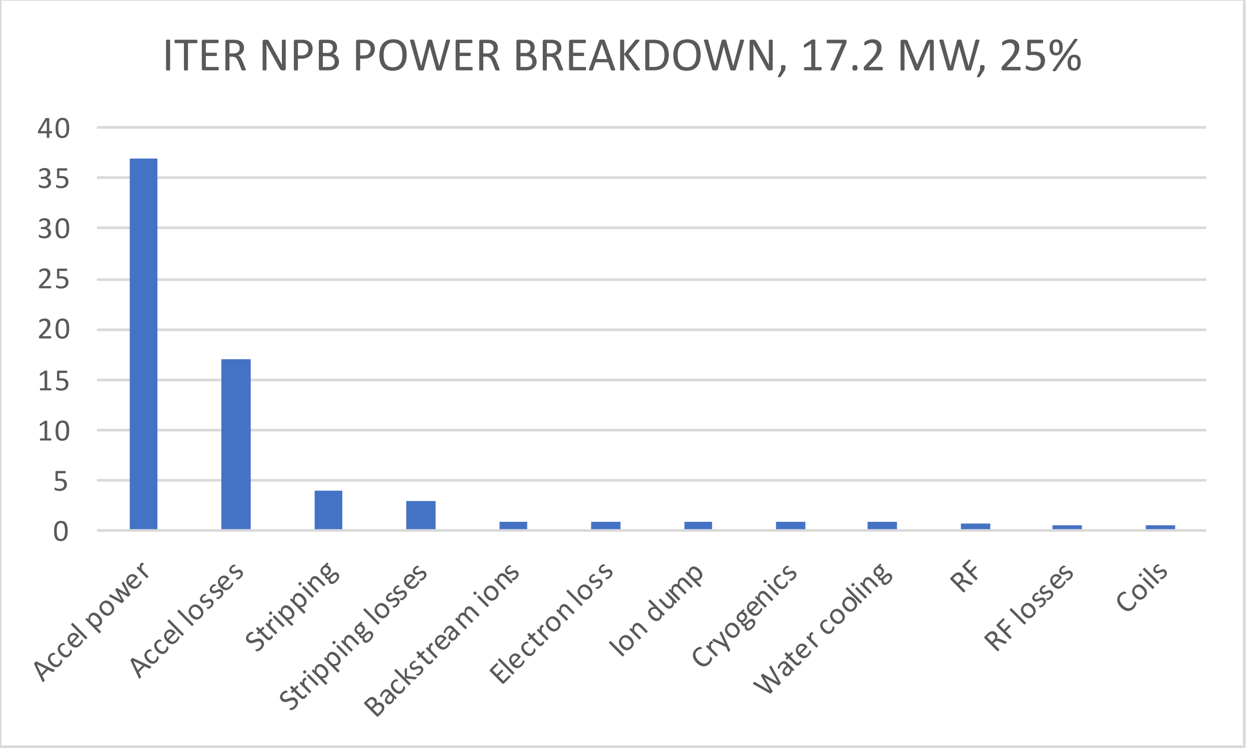
Cesium, used in the ion source, migrates over time and contaminates the grid electrodes and other components near the reactor, limiting the reactor's operation to <1-yr, for "cleaning"

The near reactor environment is also highly radioactive and unsafe for all personnel, therefore remote operation is mandatory

Cryopumps used in the neutralizers must be regenerated after ever few hours. This takes ~1.5 hrs turn-around time. Thus, duplicate NPB sources are needed as replacements/ backups, adding capital cost

The total efficiency for the NPB source is

$$\epsilon \sim 28\%$$



NEUTRAL-PARTICLE BEAM

Smaller size Tokamak reactors, using HTC magnets, could use lower beam particle energy, however the overall NPB source efficiency and system challenges are not expected to change, much, if at all

There are several identifiable upgrades that could potentially be used to improve the NPB source technology

SS electronics: impact ~ 10-20%
laser neutralizers: impact ~ 3-5%
reduced cryo-pumping: impact ~ 2%
NPB size reductions: impact – 5%

The impact on the total efficiency could potentially be significant, increasing from the present 28%, to the neighborhood of, $\epsilon \sim 50\%$

Hemsworth, R. S., and Boilson, D., AIP Conference Proceedings 1869, 1 (2017), 060001.

Hemsworth, R. S., Tanga, A., and Antoni, V., Review of Scientific Instruments 79, 2 (2008), 02C109.

NEUTRALIZED-ION BEAMs (NIBs ≠ NPBs)

Neutralized-Ion Beams could be an important, alternative capability

E_{ion} ≥ 0.2 keV – MeV's

J_{ion} ≥10's kA/cm^2 (100's x CL)

τ_{pulse} ~ 0.1-15 ms (impedance control)

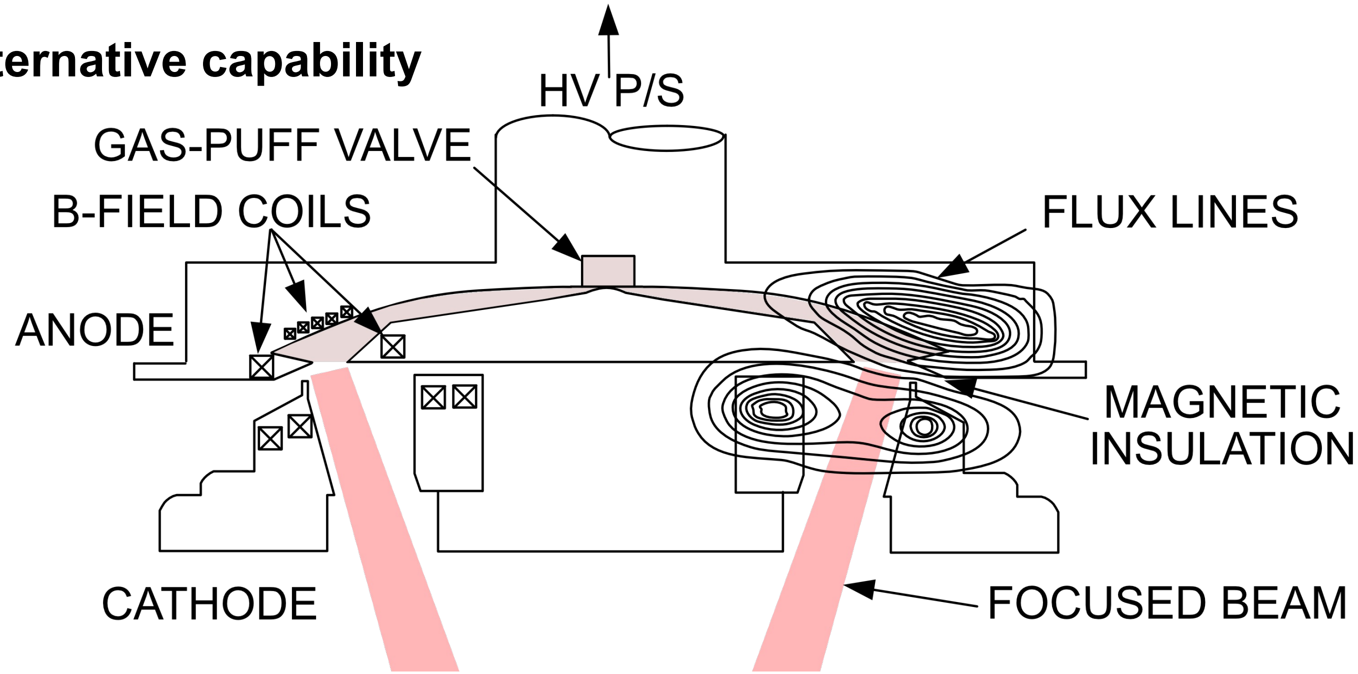
f ≈ 100's Hz (@ 250 keV, 0.4 MW)

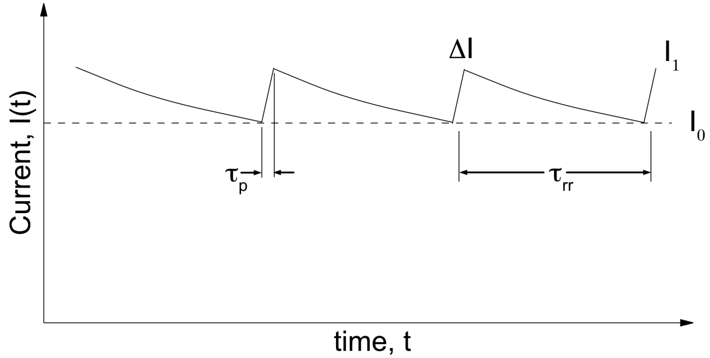
H^+, He^{+2}, B^{+3}, N^{+5}, etc. (gas species)

$r_{final}/r_{initial}$ ~ 1:10 (radial focusing)

$\Delta\Theta$ ~ 20 mRad (m's propagation)

ϵ ~ 60% (efficiency)





NIBs may also be used to provide Current Drive

Stinnett, R., et.al. Ion beam surface treatment, 10th IEEE Intl. Pulsed Power Conference (1995), vol. 1, pp. 46–55 vol.1.

NEUTRALIZED-ION BEAM HISTORY

1970’s developed for light-ion, particle-beam ICF

1980’s proposed for Tokamak heating (NPBs won)

1990’s used for Materials modification
- Quantum Manufacturing, spin-out f/SNL
- Daily operation, rep rated, 250 keV, 100’s kW

2000’s proposed for Aneutronic fusion in an FRC
- B ~ 15T and T_{ion} ~ 500 keV
- Beam output was not well matched (energy too high)
- Experiments needed reduced beam-ion energy
  - plasma had: T_{ion} ~ 10 keV, B ~ 0.2 T, ρ_{ion} ~ 30 cm

NIB INJECTION/PROPAGATION

NIB (plasma) beam injection -> $B_\perp$-field

theory developed in the 30's

refined in the 60's - 90's

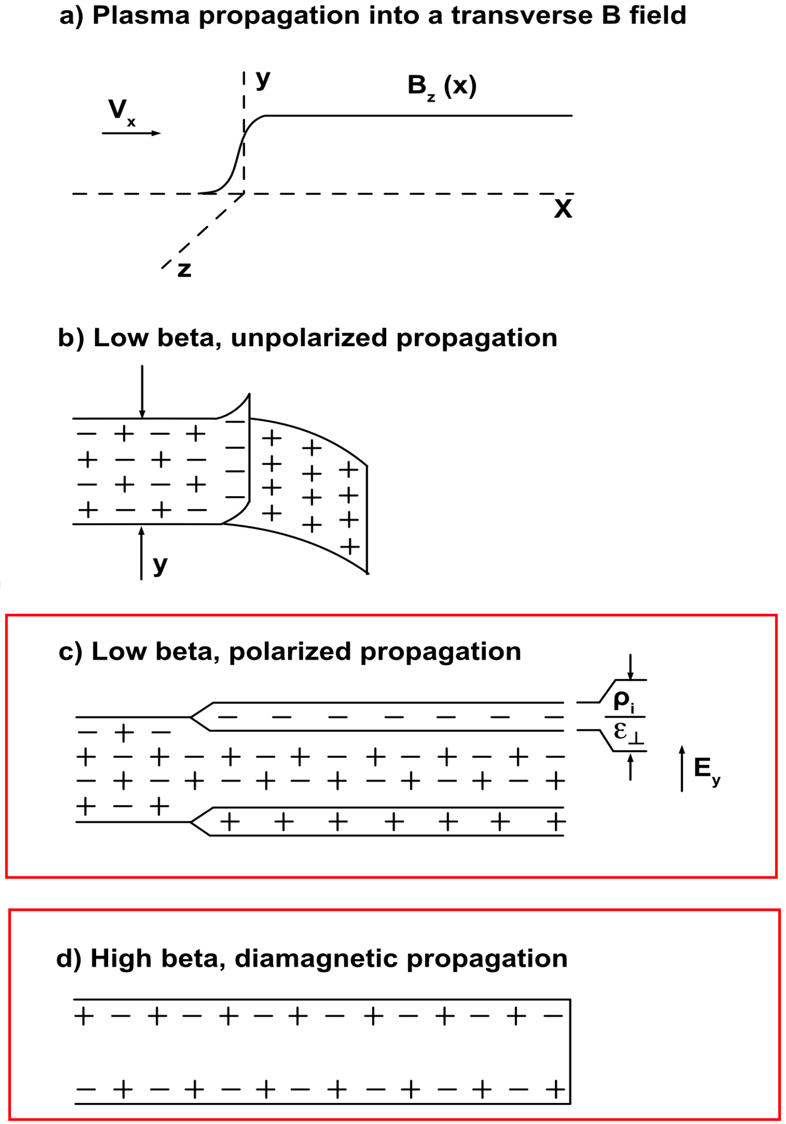
The NIB will not penetrate at **low-energy** density

The NB will propagate by the ExB drift at **medium-energy** density,

$$\epsilon = 1 + (\omega_{pi} / \Omega_{ci})^2 >> 30 = \sqrt{\frac{M_i}{m}}$$

The NIB will penetrate diamagnetically, at **high-energy** density,

$$\frac{1/2nMv^2}{B^2/2\mu_0} > 1$$



Wessel, F. J., Rostoker, N., Fisher, A., et.al. Phys.Fluids B2, 6 (1990), 1467–1473.

NEUTRALIZED-ION BEAM PROPAGATION

The physics basis is as follows

A collisionless plasma beam self-polarizes[1] in a transverse B

$$\varepsilon = 1 + (\omega_i/\Omega_i)^2 >> 30$$

Essentially this is an energy-density argument, where the Beam$_{K.E.}$ > E-field energy

$$\tfrac{1}{2}\, nMV_x^2 >> E_y^2/8\pi$$

The forward propagation of the NIB will continue at the ExB velocity

$$V_x = V_0(1 - 1/\varepsilon)$$

To prevent beam losses and filimentation[2] , the beam dimensions should be,

$$y >> \Delta y = \rho_i/\varepsilon \qquad \& \qquad y < \rho_i/2$$

1. Schmidt, G. Phys. Fluids 3, 961 (1960) & 5, 994 (1962)
2. Lindberg, L. Astrophys. Space Science 55, 203 (1978).

LIMITS TO ExB BEAM PROPAGATION

The NIB is trapped when its energy density is too low
this occurs if ϵ < 30 and is due to charge-layer erosion or beam expansion in the magnetic field

E-field shorting may also stop the beam. This may occur if the B field intersects a conducting boundary in the presence of a magnetized plasma

E-field shorting may be avoided using a high-beta beam in this case the beam propagates diamagnetically

In a Tokamak, E-field shorting is not expected, since the B-field lines are closed and since the timescales for the magnetized plasma to drift transversely or circumfrentially, are too long

Field shorting in a 250 keV, 1 μs beam

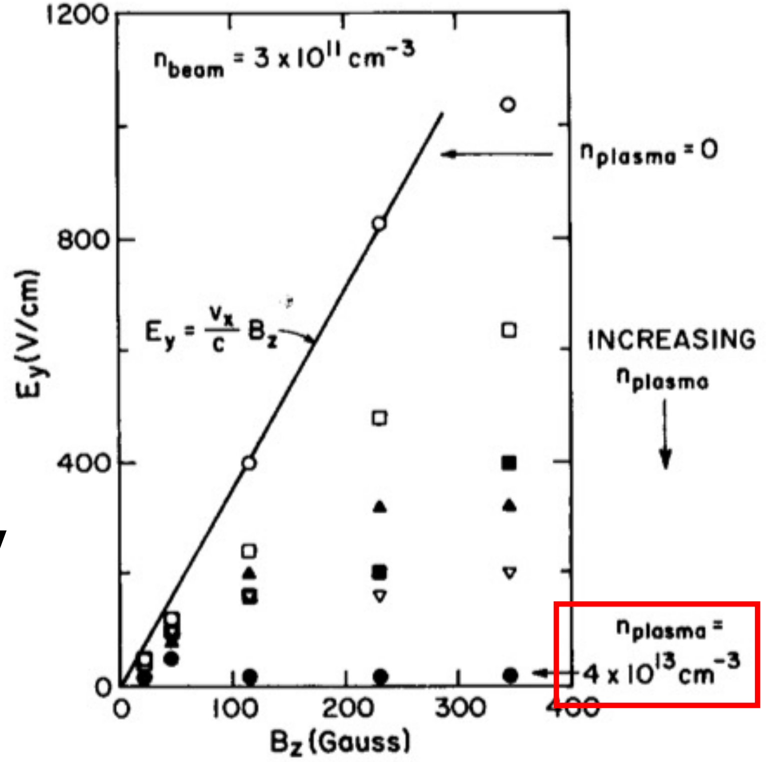
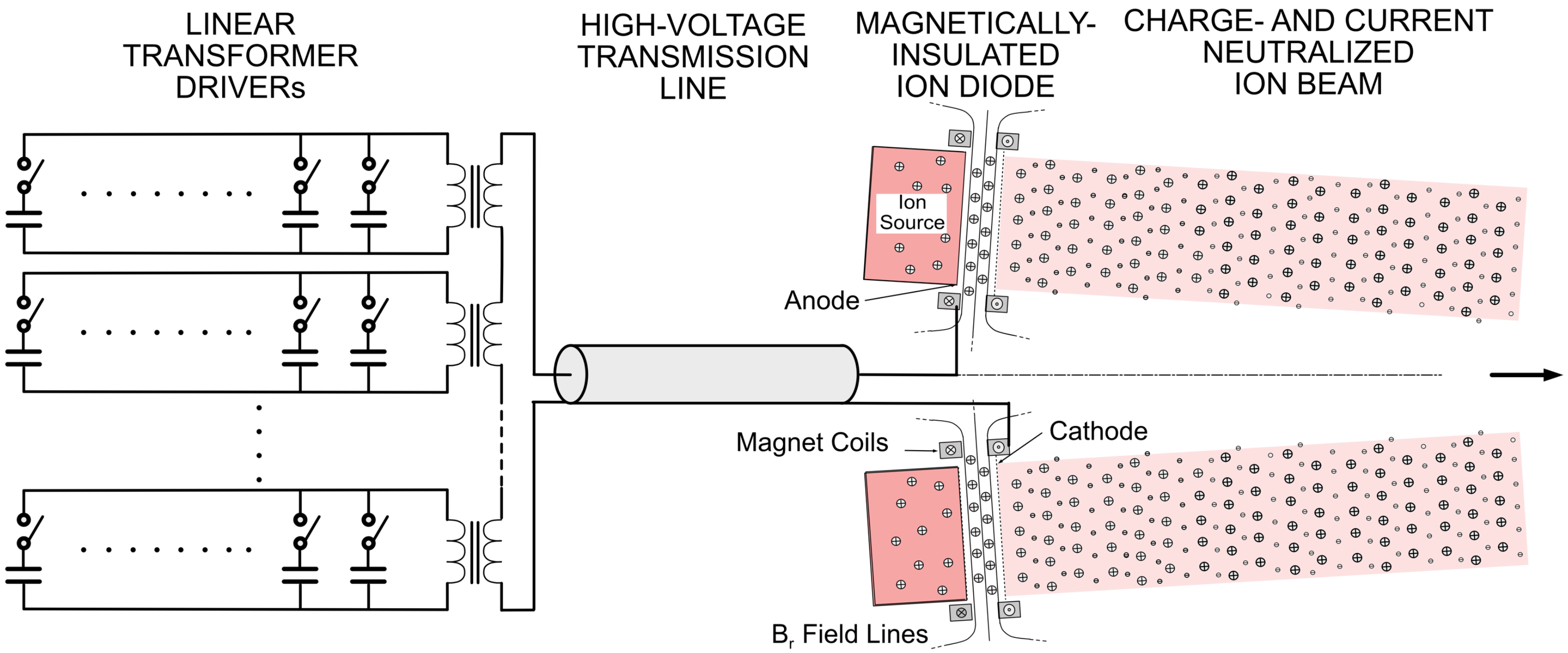


FIG. 3. Polarization electric field strength in a drifting ion beam versus transverse magnetic field strength, for various background plasma densities, n_{plasma}.

F. J. Wessel, et.al., Phys.Fluids B2, 6 (1990), 1467–1473.

NIB INJECTOR TECHNOLOGY



Compact size, low-impedance output
High efficiency electrical conversion
Uses solid-state electronic components
Metglas transformer cores
Does not require an extra pulse-compression section

Magnetically-insulated, gas-puff ion source
Pre-accelerated anode plasma
DC high voltage for particle acceleration
Superconducting B-field coils
High efficiency beam generation
Beam focusing, transport for many m's

CHALLENGES REMAIN FOR ANEUTRONIC FUSION

nature communications

Article https://doi.org/10.1038/s41467-023-36655-1

First measurements of $p^{11}B$ fusion in a magnetically confined plasma

Received: 4 November 2022

Accepted: 10 February 2023

Published online: 21 February 2023

Check for updates

R. M. Magee[1], K. Ogawa[2], T. Tajima[1,3], I. Allfrey[1], H. Gota[1], P. McCarroll[1], S. Ohdachi[2], M. Isobe[2], S. Kamio[1,3], V. Klumper[1,3], H. Nuga[2], M. Shoji[2], S. Ziaei[1], M. W. Binderbauer[1] & M. Osakabe[2]

Proton-boron ($p^{11}B$) fusion is an attractive potential energy source but technically challenging to implement. Developing techniques to realize its potential requires first developing the experimental capability to produce $p^{11}B$ fusion in the magnetically-confined, thermonuclear plasma environment. Here we report clear experimental measurements supported by simulation of $p^{11}B$ fusion with high-energy neutral beams and boron powder injection in a high-temperature fusion plasma (the Large Helical Device) that have resulted in diagnostically significant levels of alpha particle emission. The injection of boron powder into the plasma edge results in boron accumulation in the core. Three 2 MW, 160 kV hydrogen neutral beam injectors create a large population of well-confined, high -energy protons to react with the boron plasma. The fusion products, MeV alpha particles, are measured with a custom designed particle detector which gives a fusion rate in very good relative agreement with calculations of the global rate. This is the first such realization of $p^{11}B$ fusion in a magnetically confined plasma.

1. TAE Technologies, Foothill Ranch, CA
2. National Inst. Fusion Science, Toki, Japan,
3. University CA, Irvine, CA

2 H^+ NPBs,
3 H^- NPBs,
^{11}B (powder)

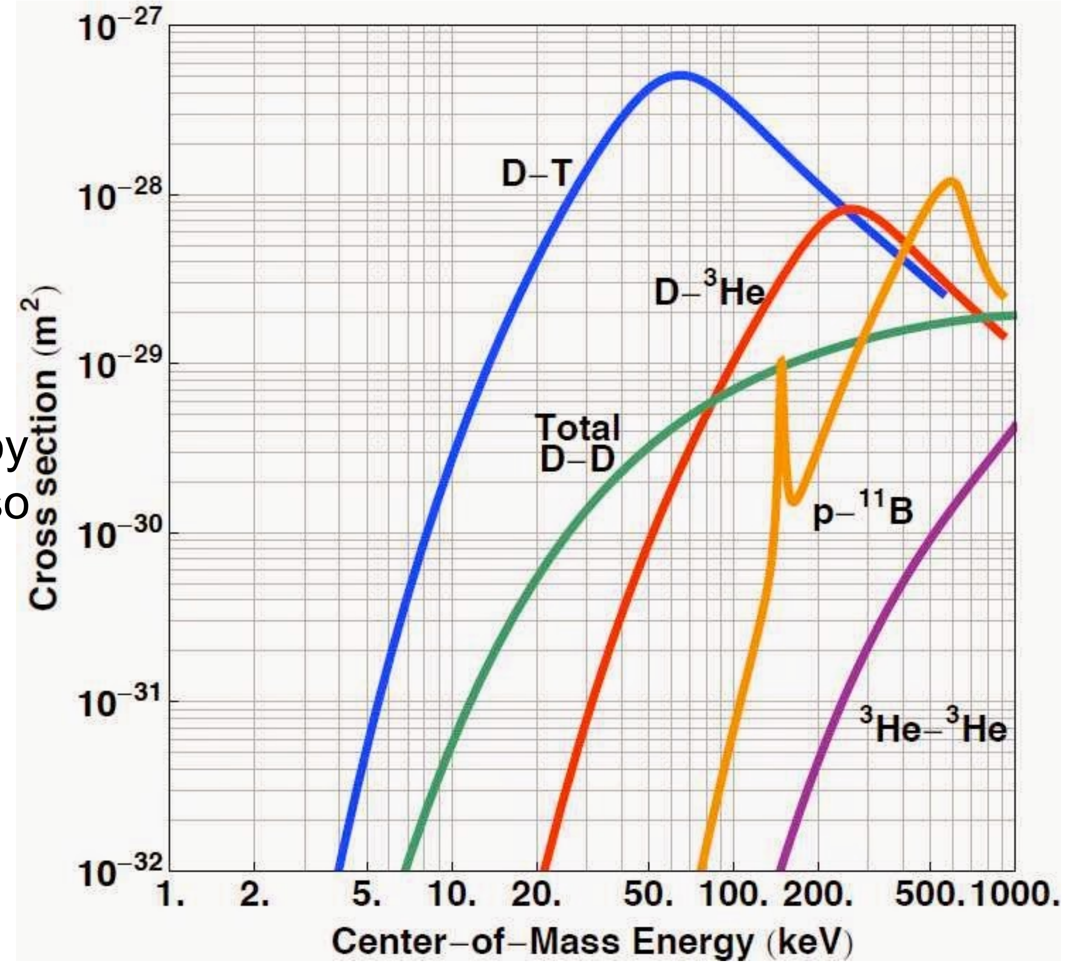
NIBs MAY ALSO ADDRESS LIMITED AVAILABILITY OF FUSION FUELS

Neutralized-ion beams could be used to both enable aneutronic fusion, as well as provide fuel feedstock for D + T and D + He3 fusion

Because of their high-energy ion output, NIBs could be used to heat DD to 500+ keV temperatures, and thereby enable scarce fusion fuels to be actively bred, while also generating electric power

$$\begin{aligned} D + D \quad &\rightarrow (50\%)\ T + p \\ &\rightarrow (50\%)\ {}^{3}He + n \end{aligned}$$

tritium and helium3



ENGINEERING ESTIMATES FOR THE NPB vs. NIB METRICS

PARAMETER	NPB (D^0)	NIB ($D^+ + e^-$)	COMMENTS
Ion particle energy (MeV)	0.1 – 1	0.1 - 1	
Beam power density (W/m^2)	10	**1,000**	NPB unfocused, NIB focused 0.2-m dia.
Total efficiency (%)	35	**75**	Solid state electronics, minimal gas flow & cryogenics
Gas load (cryogenic pumps)	Very High	Very Low	Downstream neutralizers are not needed with NIBs
Cost ($/W)	4	**1**	Internal component count is much smaller for the NIB
Accelerator Size (m^3/MW)	15	5	Not including the prime- & source-power supplies
Beam injection aperture (m^2)	1.5	0.1	Beam focusing with a NIB
System lifetime	3-4	3-4	TRLs for both are significantly challenged

CONCLUSIONS

Neutral-particle beam technology can still be improved, even after 40+ years of continuous R&D.
Specific areas include gas handling, beam neutralization, and the use of SS electronics.
These improvements must address the system lifetime, efficiency, and the volumetric size issues.

What vendors can presently supply negative-ion source, NPBs in the U.S.?
Supply chain issues need to be addressed, because it will take many years to establish.
The US is an active participant in the ITER Project, so we do have access to this technology.

In contrast, the pulsed-power technology used in NIBs is already well established in the U.S.
Existing NIB designs are readily available and well characterized.
However, there may still be issues related to the NIB source lifetime.

CONCLUSIONS

The performance of NIBs do compare favorably to that of NPBs. NIBs should be developed as a backup to NPBs, or an alternative approach to plasma heating, current drive, and fueling.

NIBs can provide much higher ion energy, with a beam-energy density >> NPBs. Their efficiency is also, much higher and they are far smaller size and lower cost.

The TRL for NIB technology is only slightly lower than for NPBs. For both technologies, the use of SS power electronics may be expected to dramatically improve performance/efficiency.

Moreover, the physics of beam injection, propagation, and trapping appears well established.
Advanced PIC/Hybrid simulations would establish confidence in these methods.
Experiments should also be performed on toroidal devices.

NIB technology also addresses advanced aneutronic fusion, as potential heating and fueling sources.

Several promising aneutronic-fusion concepts exist,
particularly in a non-toroidal geometry and with high-magnetic beta.
NIBs are readily scalable and can address the 500+ keV plasma temperature regime.

NIBs are also potentially enabling for heavy-ion ICF, if combined with induction-linac technologies.

REFERENCES

NPBs

1. Jassby, D. Neutral-beam-driven tokamak fusion reactors. Nuclear Fusion 17, 2 (1977), 309.
2. Hemsworth, R. S., and Boilson, D., AIP Conference Proceedings 1869, 1 (2017), 060001.
3. Kojima, A., Umeda, et.al. Powerful negative ion beams for JT-60sa and ITER. Nuclear Fusion 55, 6 (2015), 063006.
4. Bacal, M., and Wada, M. Negative ion source operation with D2. Plas.Sources Sci.&Tech. 29, 3 (2020), 033001.
5. Shirai, H., Barabaschi, P., Kamada, Y., Recent progress of the JT-60sa Project. Nuclear Fusion 57, 10 (2017), 102002.

ExB

6. Chapman, S., and Ferraro, V. C. A. A new theory of magnetic storms. Terr. Mag. and Atmos. Electricity 36, 2 (1931), 77–97.
7. Schmidt, G. Nonadiabatic particle motion in axialsymmetric fields. The Physics of Fluids 5, 8 (1962), 994–1002.
8. Bostick, W. H. Experimental study of ionized matter projected across a magnetic field. Phys. Rev. 104 (1956), 292–299.
9. Lindberg, L. Plasma flow in a curved magnetic field. Astrophys. Space Sci. 55, 1 (1978), 203–225.
10. Wessel, F. J., Rostoker, N., Fisher, A., et.al.Propagation of neutralized plasma beams. Phys.Fluids B2, 6 (1990), 1467–1473.

NIBs

11. Dreike, P., Eichenberger, C., Humphries, S., and Sudan, R. Magnetically insulated diode. Jour. App. Phys. 47, 1 (1976), 85–87.
12. Greenspan, M. A., Pal, R., Hammer, D. A., and Humphries, S. Applied-Bθ magnetically insulated ion diode. App.Phys.Lett. 37, 2 (1980), 248–250.
13. Greenly, J. B., Ueda, M., Rondeau, G. D., and Hammer, D. A. MID gas-breakdown plasma anode. Jour. App. Phys. 63, 6 (1988), 1872–1876.
14. Stinnett, R., Buchheit, R., Neau, E., and et.al. Ion beam surface treatment: 10th IEEE Intl. Pul.Power Conf.(1995), vol. 1, pp. 46–55 vol.1.

LTDs

15. Mazarakis, M. G., Fowler, W. E., Kim, et.al. High current, 0.5-ma, fast, 100-ns, LTD experiments. Phys. Rev. ST Accel. Beams 12 (2009), 050401.
16. Kim, A. A., Mazarakis, M. G., Sinebryukhov, V. A., and et. al. 1-MA LTD stages. Phys. Rev. Special Topics 12 (2009), 050402.
17. Humphries, S., Anderson, R. J. M., Freeman, J. R., and Greenly, J. Intense ion beam injectors. Rev. Sci. Inst. 52, 2 (2022/10/14 1981), 162–171.

Fusion

18. Yushmanov, E. Efficiency of the magneto-electrostatic trap. Nuclear Fusion 21, 3 (1981), 329.
19. Sheffield, J. The physics of an attractive magnetic fusion reactor. Nuclear Fusion 26, 12 (1986), 1739–1740.
20. Handley, M. C., Slesinski, D., and Hsu, S. C. Potential early markets for fusion energy. Journal of Fusion Energy 40, 2 (2021), 18.
21. Wurzel, S. E., and Hsu, S. C. Progress toward fusion energy breakeven and gain. Physics of Plasmas 29, 6 (2022), 062103.